Studies of Charge Collection in Diamond-Based Particle Detectors at the LHC

Student: Jared Smith, First-Year Undergraduate

Faculty Adviser: Dr. Stefan Spanier

The Noble Prize in 2013 was awarded to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider." The announcement by the ATLAS and CMS experiments took place on 4 July, 2012.

The mechanism was first proposed by those authors in 1964 in two papers published independently. It explains how the force responsible for the decay of atom nuclei is much weaker than electromagnetism, but it is better known as the mechanism that endows fundamental particles with mass. The new idea forms an essential part of the Standard Model of particle physics. As was pointed out by Higgs, a key prediction of the idea is the existence of a massive, so-called Higgs boson. The Standard Model describes the fundamental particles from which we, and all the visible matter in the Universe, are made, along with the interactions that govern their behavior. It is a remarkably successful theory that has been thoroughly tested by experiment over many years, and the Higgs particle was the last remaining piece of the model to be experimentally verified. Nevertheless, the theory does not immediately apply to energies that exceed those of the LHC but were certainly involved during the evolution of the Universe (Big Bang). An obvious reason could be that not-yet discovered forces with their own new particles exist. Furthermore, the Standard Model does not deal with the gravitational force. Some models including the gravitational force actually predict that Micro-Black Holes could even be produced in the particle accelerator.

The way to probe such shortcomings is to either observe behavior in particle reactions different from the one as predicted by the Standard Model, or to explicitly create those new particles at higher and higher energies. As such effects and appearances are expected to be rare the initial particle beam needs to have higher and higher intensity, and the rate at which collisions occur needs to increase. This presents new challenges on the particle detectors: they have to be very radiation hard and fast, and provide with high efficiency location and energy of reaction products. The detectors closest to the LHC beam provide essential measurements of charged particle trajectories and are particularly exposed to the radiation from the LHC.

Studying detectors that have these key characteristics is the focus of my research. More specifically, Chemical Vapor Deposition (CVD) diamonds show promising results for the next-generation detectors needed closest to the LHC beam. In coordination with the High Energy Physics Group of the University and Dr. Stefan Spanier, I have spent the last several months studying several of our own CVD diamonds on a test-stand I calibrated and personally assembled in our laboratory. Using this test-stand and several diamonds of various irradiation levels, I have collected and analyzed a substantial amount of data that has revealed much about the radiation hardness of diamonds when damaged with proton irradiation. Presented here are the results of this research.

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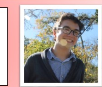
Jared Smith, First-Year Undergraduate
University of Tennessee, Department of Physics and Astronomy

Contact Information
- jsmit359@utk.edu
- www.jared-smith.net
- (865) 274-3800



Background

Introduction

The Noble Prize in 2013 was awarded to François Englert and Peter W. Higgs **"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS**

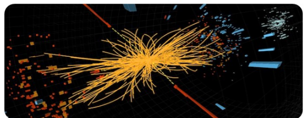


Figure 1: CMS Event Display depicting Higgs Event(photo credit: CERN)

This mechanism explains how the force responsible for the decay of atom nuclei is much weaker than electromagnetism, but it is better known as the mechanism that endows fundamental particles with mass. The new idea forms an essential part of the Standard Model of particle physics. The **Standard Model describes the fundamental particles from which we, and all the visible matter in the Universe, are made**, along with the interactions that govern their behavior. The model does not immediately apply to energies that exceed those of the LHC but were certainly involved during the evolution of the Universe (Big Bang). An obvious reason could be that **not-yet discovered forces with their own new particles exist**. Furthermore, the Standard Model does not deal with the gravitational force. The way to probe such shortcomings is to either observe behavior in particle reactions different from the one as predicted by the Standard Model, or to explicitly create those new particles at higher and higher energies. As such effects and appearances are expected to be rare the initial particle beam needs to have higher and higher intensity, and the rate at which collisions occur needs to increase. This presents new challenges on the particle detectors: they have to be **very radiation hard and fast, and provide with high efficiency location and energy of reaction products**. The detectors closest to the LHC beam provide essential measurements of charged particle trajectories and are particularly exposed to the radiation from the LHC. **This is where my work comes in.** As you will see in this presentation, my work closely examines **the radiation hardness qualities of diamond**, a new and advancing material of interest in building suitable and long-lasting detectors for the LHC.

The LHC

The LHC, or Large Hadron Collider, is the world's largest particle accelerator, serving the needs of hundreds of collaborations and groups of scientists from all over the world. Made up of several different complex rings and testing sites, the LHC is located in Geneva, Switzerland, and has been one of the leading frontiers of discovery in physics over the last century. However, as stated before, CMS and ATLAS, where most of the data comes from, must be capable of probing energies at higher and higher levels in order to discover more particles and fundamental forces. Doing this requires detectors that are subjected to larger amounts of radiation as the energy scales rise. Currently, silicon detectors are the primary material used in detecting particles within CMS; unfortunately, silicon is not as radiation hard as we would prefer, so newer materials such as diamond and more advanced materials with a large quality of radiation hardness are being tested. Ideally, these diamond detectors will be installed in the LHC in one of the upcoming upgrades to the detector. Principally, that is what I am investigating.

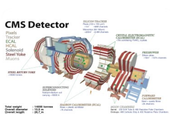


Figure 2: A look inside CMS.

Figure 3: CMS from the outside.

CVD Diamond Detectors

In my work, I use CVD diamonds for the detecting material. CVD stands for chemical vapor depositions, and is the process by which these artificial diamonds are created. The process by which they are created is far less important than how CVD diamonds function as detectors. Essentially, when we study the charge collection of these diamonds, we are studying the **electron drift** of the charges when an alpha particle is shot through the diamond. When this occurs, the alpha particles create electron-hole pairs in the diamond lattice, that drift in opposite directions when the alpha particles collide with atoms in the diamond. As each charge moves through the diamond, an electronic signal is produced that can be measured and counted as an event at a certain bias voltage through the diamond. It is the plotting of these bias voltages against the mean peak value of signal voltage at that bias that I will plot in my data. Ideally, all charges that enter the detector should leave, without getting trapped, and regardless of the radiation damage to the diamond; however, because of the damage, not all charges make it through.

General Properties:
- Strength of material → rigidity of it's lattice & relative small mass of carbon atom
- Highest thermal conductivity of any known material
- **Electrical properties → Bandgap of 5.45 eV**
- High resistivity → $10^{13} - 10^{16}\ \Omega cm$
- High refractive index (n=2.419)
- **Known to be radiation hard.**

Figure 4: Final Product – CVD Diamonds

Radiation Damage

NOTE: This is for proton irradiation, we are studying the effects of neutron irradiation on diamonds, and our ultimate goal is to reproduce this famous curve except that we will use neutron irradiation. On this note, radiation damage affects the charge collection distance, lowering it, which weakens the signal received by a displaced charge in the diamond. This effect is highly studied by the RD-42 Collaboration based out of CERN.

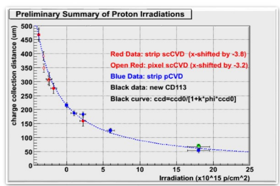


Figure 5: RD-42 Damage Curve for CVD Diamonds

Experiment

Objectives

I. Analyze charge collection of both non-damaged and damaged diamonds.
II. Determine Charge collection efficiencies in various conditions.
III. Establish a reliable test-stand for diamond detector.
IV. Eventually, measure rate dependence and light dependence of diamonds.

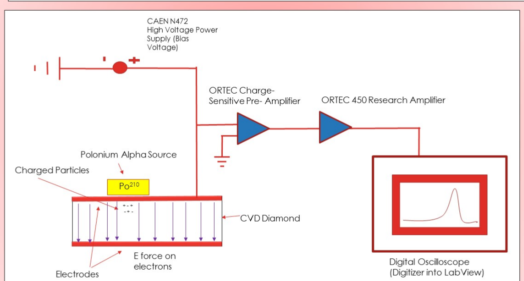
Apparatus

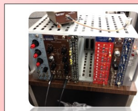
One of the primary goals of my research is to set up a reliable test stand for measuring the properties of diamonds.
The following materials primarily compose the test stand:

- NI-5154 Digitizer
- ORTEC Charge-Sensitive Pre-Amplifier
- CAEN High Voltage Power Supply
- ORTEC 450 Research Amplifier
- CVD Diamonds (S130 and S131)
- Polonium-210 Alpha Source
- Light-tight box (Fabricated box to prevent light from shaking charges off of the diamond

Specifications: the amplifier gain always stayed constant and was calculated beforehand to produce an optimal signal range for the digitizer. A minimum amount of BNC cables and connectors were used to minimize gain. LabView software was used for data analysis, as well as ROOT, CERN's framework for particle physics data analysis.

Test-Stand





Figures 6, 7: Crate housing electronics, Inside detector with yellow alpha source and diamond on top.

Figures 7, 8: Digitizer connected to crate and computer with LabView, light-tight box.

Diamonds S130 and S131

S130
- No irradiation
- Thickness: 536 microns
- Dimensions: 4.6 X 4.6 mm
- Bandgap of 5.4 eV

S131
- Irradiation of 0.5 X 10^{14} neutrons/cm^2
- Thickness: ≈500 microns
- Dimensions: Roughly the same size as S130: ≈ 4.6 X 4.6 mm
- Bandgap of 5.4 eV

Tests Run

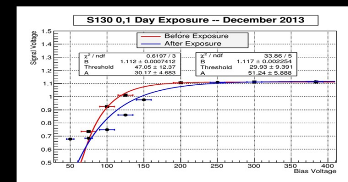
Using two diamonds, S130 and S131, and a Polonium 210 alpha source, I used the test set-up from the previous slide to perform the following tests:
S130 and S131:

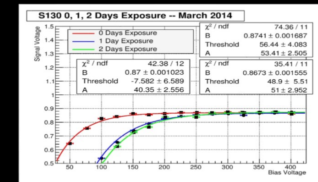
Standard Exposure:
Measure charge collection before exposure to alpha particles, then measure again after exposed for roughly 24 hours.

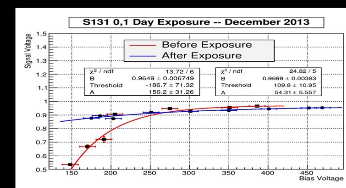
Light-Tight and Voltage:
Measure charge collection with the detector in a "light-tight" box and by leaving the bias voltage across diamond at a constant 500V during exposure periods.

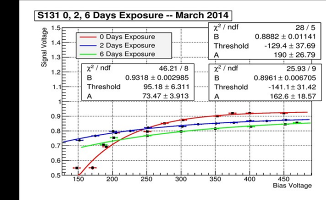
Standard Exposure occurred in December 2013 and March 2014
I took account for the decay of the polonium source when reproducing the S131 test from December in March by extending the time of exposure to account for the source's decay.

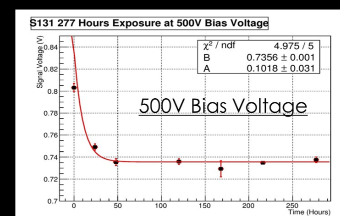
Results











S130	% Charge Collection	Threshold/Trigger-Level
Standard Exposure – December 2013		
After 0 Days	≈100%	0.1 V
After ≈1 Day	≈100%	0.1 V
Light-Tight/Voltage – March 2014		
After 0 Days	100%	0.1 V
After ≈1 Day	99.5%	0.1 V
After ≈2 Days	99.2%	0.2 V

S131	% Charge Collection	Threshold/Trigger-Level
Standard Exposure Test 1 – December 2013		
After 0 Days	100%	0.1 V
After ≈1.1 days	99.5%	0.2 V
Standard Exposure Test 2 – March 2014		
After 0 Days	100%	0.2
After ≈1.7 Days	96.2%	0.2
After ≈5.9 Days	95.3%	0.4
Light-Tight/Voltage – March 2014		
After 0 Days	100%	0.25
After ≈1 Day	93.6%	0.25
After ≈2 Days	91.9%	0.3
After ≈5 Days (500 V)	91.3%	0.1
After ≈6 Days (500 V)	91.1%	0.1
After ≈8 Days (500 V)	91.3%	0.1
After ≈11 Days (500V)	91.9%	0.1

When Calculating Percent Charge Collection:

Take into account:
Source: Polonium-210
5.30438 MeV alpha particles generated by Polonium[210] source
1 electron-hole pair generated per 13 eV

To get the % charge collection: must divide amount of charge collected at certain bias voltage by total amount of charge that *should* be collected overall.

However, this is difficult without knowing the specific qualities of the electronics and the setup; therefore, I will normalize the max collection to the saturation value given by the baseline of each test.

$E - H\ pairs = \frac{1^{e^-}}{13\ eV} * 5.30438\ MeV = 408{,}030\ (e - h\frac{pairs}{particle})$
→ Total charge that should be collected.

Conclusion

- **Overall, it is clear that as a diamond is more heavily irradiated, the charge collection efficiency is lowered.**
- **Furthermore, over time that the diamond is left under constant voltage and exposure to radiation, the efficiency is also lowered.**
- Some unknowns:
  - We believe there may be a reverse field created immediately after the voltage is taken off the diamond where the electrons and holes are pulled in the opposite direction.
  - What about 3D diamond detectors?
- **It is clear that diamonds will not be used as the next upgrade of the detectors in the LHC, but they still have many other uses that could be explained in an entire other presentation.**

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